Diagnostics for High Power Accelerator Machine Protection Systems

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Facility for Rare Isotope Beams
Michigan State University

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During the past decade, proton accelerators raised beam power to ~ 1 MW
- SNS (USA): 1 MW pulsed; SRF linac/accumulator
- J-PARC (Japan): 0.3 MW pulsed; warm linac/RCS
- PSI (Switzerland): 1.4 MW CW; cyclotron
- 5 MW in design (ESS)

Heavy Ion linacs are approaching 0.5 MW
- FRIB 400 kW
- From proton to $^{238}$U

Stored energy in proton colliders is unprecedented
- 1-3 MJ (SPS,RHIC,HERA,TEVATRON)
- 140 MJ (LHC) – design 360 MJ

Diagnostics for High Power Accelerator Machine Protection Systems
Key technologies driving the push

• RF and large scale cryogenics
• Ion sources, RFQs, LEBT
• High power collimators, charge strippers
• Rapid-cycling booster synchrotrons
• High power targets and radiation-tolerant magnets
• Loss detection and MPS
Machine Protection Systems

- **Exist**
  - to prevent or minimize prompt and long-term damage to accelerator and experimental instrumentation,
  - to minimize the number of false-trips that limit production,
  - and to provide evidence of failures or fault events when interlocks occur

- **Must respond to many types of events**
  - Hardware failures
  - Control system failures
  - Operational and administrative failures
  - Beam instabilities and other unforeseen events

- **Time scales are encompass Fast Protection and Run Permit Systems**
  - FPS protects against prompt damage at several to 100s $\mu$s
  - RPS operates at milliseconds to many seconds; verifies machine state and external conditions

- **MPS must be flexible to cope with wide ranging operating modes**
Time scale for component failure from errant beams

Stopping ranges of beam particles in materials vary with species, energy, and target material.

1. High energy proton or hadron beams create cascades that deposit energy deeply (m’s).

2. Low energy heavy ion beams deposit energy mainly on surfaces (μm’s to mm’s).

3. Component failure results from fast deposition, thermal transport, and material stress.

(Zhang)
### Errant beam detection times

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PSI</td>
<td>H⁺</td>
<td>590</td>
<td>1.3</td>
<td>few 100</td>
</tr>
<tr>
<td>SNS</td>
<td>H⁻/H⁺</td>
<td>1000</td>
<td>1-2</td>
<td>5-10*</td>
</tr>
<tr>
<td>ESS</td>
<td>H⁻/H⁺</td>
<td>2000</td>
<td>5</td>
<td>1-2</td>
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<tr>
<td>SPIRAL-2</td>
<td>D/Hi</td>
<td>20</td>
<td>0.2</td>
<td>10</td>
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<tr>
<td>FRIB</td>
<td>HI</td>
<td>200</td>
<td>0.4</td>
<td>10</td>
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<tr>
<td>JPARC-MR</td>
<td>H⁺</td>
<td>3 × 10⁴</td>
<td>0.75</td>
<td>10</td>
</tr>
<tr>
<td>LHC</td>
<td>H⁺</td>
<td>7 × 10⁶</td>
<td>4 × 10⁶</td>
<td>40</td>
</tr>
</tbody>
</table>

*25 µs response time (design)
Slow beam losses

Leads to radioactivation, cryogenic thermal loading, and SRF cavity degradation.

Previous experience indicates 1 W/m losses generates 100 mRem/hr activation.
LANSCE: 100 mRem/hr @ 780 kW
SNS: 30-40 mRem/hr @ 1 MW
Slow beam losses

Leads to radioactivation, cryogenic thermal loading, and SRF cavity degradation.

Previous experience indicates 1 W/m losses generates 100 mRem/hr activation.
LANSCE : 100 mRem/hr @ 780 kW
SNS : 30-40 mRem/hr @ 1 MW

Slow losses have multiple sources.
E.g. intra-beam stripping losses of H⁻ beam in SNS.

Line fits are expected losses from intra-beam stripping.

Strong focusing
Weak focusing

Diagnostics for High Power Accelerator Machine Protection Systems
Challenges and Opportunities

- Dynamic range of intensities and time scales (beam current, pulse formats, fast/slow losses)
- Contend with high radiation field and EMI backgrounds
- Need for fast and robust reporting and control networks, with low error rates
- Simulation and modeling of radiation fields from slow and fast losses; loss patterns from specific fault events
MPS inputs

- Beam loss monitors
  - Prompt radiation fields from accelerator components – rf cavities, distribution lines, rf sources
  - Secondary particle fields produced by beam collisions
    » Gammas, neutrons, hadronic showers

- Direct beam measurements
  - Peak and average beam current or intensity
  - Beam orbit
  - Beam halo
  - Micro pulse duration
  - Spot size

- Vacuum monitoring
  - Fast leak detection
  - Slow drift in background pressure

- Cryogenic and SRF monitors
  - Thermal loads
  - Quench detection
  - LLRF

- Magnet power supplies
  - DCCTs

- Machine status
  - Beam interlocks
  - Power limiting devices
Gamma and neutron production

- Secondary radiation produced by primary beam particle collisions with vacuum chamber or residual gases.
- For low and medium energy beams, the background is primarily gammas and neutrons.
- Production yields are have strong energy dependence.
Energy dependent radiation fields for 1 W/m loss (ESS)

Power density (Gy/s) at 200 MeV

Power density (Gy/s) at 2 GeV

(Tchelidze)
Radiation transport models are essential to understand the background

- Simulations with two codes are implemented and compared
  - Detailed two-cryomodule geometry model implemented in GEANT4. γ dose is calculated as an average around cryomodule
  - Simplified homogenous tunnel model implemented in PHITS. γ dose is calculated in an “ion chamber” 1 foot below each segment

- Results from these two models are comparable

(Diagnostics for High Power Accelerator Machine Protection Systems, Slide 13)
Crosstalk effects confuse spatial location and mask events

Diagnostics for High Power Accelerator Machine Protection Systems

Neutron induced by 1 W/m $^{18}$O loss

Flux at box 4 by LS1 loss
Flux at box 4 by LS2 loss
Flux at box 4 by LS3 loss

<table>
<thead>
<tr>
<th>Neutron induced by 1 W/m $^{18}$O loss</th>
<th>Flux at box 4 by LS1 loss</th>
<th>Flux at box 4 by LS2 loss</th>
<th>Flux at box 4 by LS3 loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>n/cm²/sec</td>
<td>$1.03 \times 10^5$</td>
<td>$5.81 \times 10^5$</td>
<td>$3.2 \times 10^6$</td>
</tr>
</tbody>
</table>

Beam Energy (MeV/u)

Radiation dose in ion chamber (rad/hr)

Proton Beam □
Oxygen beam △
Uranium beam □
Crosstalk effects confuse spatial location and mask events

Diagnostics for High Power Accelerator Machine Protection Systems

Neutron induced by 1 W/m $^{18}$O loss

Flux at box 4 by LS1 loss

Flux at box 4 by LS2 loss

Flux at box 4 by LS3 loss

n/cm$^2$/sec

1.03 $\times$ 10$^5$

5.81 $\times$ 10$^5$

3.2 $\times$ 10$^6$

(Liu)
Loss patterns from beam dynamics simulations

- To assess risk from chronic and infrequent, fast loss events, beam spill patterns can be generated and analyzed.

- Spill pattern maps can assist in optimum placement of beam loss monitors and passive protection devices.

- Realistic lattice errors and beam distributions can place bounds on loss from halo and core interception.
  - Still very model dependent.

- Spill patterns from component errors or faults can assist post-mortem analyzes.

- Machine learning frameworks are being developed to optimize loss monitor networks and to reconstruct events.
Superconducting linac starts with 3 $\beta=0.041$ cryomodules
- Each module has 4 cavities and 2 solenoids

First cavity in the linac 1 failure

All beam lost in the first 3 CMs
- Beam loss on a cavity ~40 W
- Beam loss on a pipe area ~500 W

Example: Beam Loss Distributions with Single Cavity Failure (FRIB)

Normal case
- Aperture in black
- 100% beam envelope
- 90% beam envelope

Fault case
- Aperture in black
- 100% beam envelope
- 90% beam envelope

Beam loss on cavity (W): 39 1.1 34 5 3
Beam loss on pipe (W): 77 485 5.5 109

(Zhao)
Distributed and localized losses inform thermal loading in SRF cavities

(source M. Jarosz)
Ionization Chambers

- Ionization chambers are the main type of loss monitors used in hadron machines.
- Gas-filled chambers containing an electrode pair with biasing high voltage.
- Operated in ‘ionization’ mode, the detector is insensitive to HV fluctuations.
- Small chambers are installed along specific components and provide adequate spatial resolution.
- Long chambers (LIONs, PLICs) provide wide coverage but lack spatial resolution (except for some pulsed machine applications)
SNS-type ionization chamber

133 cm³ Ar gas
Typical bias 1 kV
Sensitivity 70 nC/rad
Response time ~1-2 μs

R.L. Witkover
D. Gassner
LHC-type ionization chamber

- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 µs)
  - Very large dynamic range (> $10^6$)
- There are ~3600 chambers distributed over the ring

1.5 L volume - 50-cm long, 9-cm diameter
100 mbar overpressure N$_2$
0.5-mm separated Al plates
1500 V bias (end-to-end)

Sensitivity ~ 54 µC/Gy
Response time ~300 ns $e^-$, 80 µs ions

R. Schmidt
Secondary emission monitors (SEM)

Less sensitive than IC’s to gammas

Radiation tolerant (Ti SEY shows excellent linearity over integrated dose range)

Complement high sensitivity monitor to extend dynamic range near critical devices
Secondary emission monitors (SEM)

Less sensitive than IC’s to gammas

Radiation tolerant (Ti SEY shows excellent linearity over integrated dose range)

Complement high sensitivity monitor to extend dynamic range near critical devices
Scintillation based detectors

- Typically employ photomultiplier tubes for high gain ($10^5$-$10^8$) with applied HV
- Many types of scintillators fluoresce under gamma bombardment
- Li- or B- doped plastic scintillators respond to neutrons
- Additional moderation increases sensitivity at the expense of time response.

SNS Fast Detector

Sensitivity tuned with bias

SNS Neutron chamber (SBLM)
Differential Radiation Loss Monitoring

- Background subtraction techniques improve loss resolution along waveform
- Implemented in software, too slow for fast MPS
- FPGA implementation could service fast MPS

Collimated BLM – lead shielded with window, angle selectivity of gammas

Dual BLM – two scintillator based detectors, one with enhanced neutron sensitivity

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New schemes seek to detect losses in cryogenic environments

- Detection of losses within cryomodules can help to minimize damage to cavity surfaces and to prevent quenching of magnets with high stored energy

- Recent work at LHC and Fermilab
  - CVD diamond, silicon
    » Cryogenic monitoring near magnet windings (1.9 K)
    » Slow losses with sensitivities 0.1-10 mGy/s, response time < 1ms
    » Fast beam halo loss detection
    » Response times 2.5 ns (Si), 3.6 ns (diamond) to Minimum Ionizing Particles
    » Signal degradation over 20 year integrated dose is 25x (Si) and 14x (diamond)
  - LHe ionization chamber
    » Limited response to slow losses (> ~200µs)
    » Radiation tolerant – self-healing material
    » 200 V/mm bias yields ~0.1 fC/cm/MIP
    » Fermilab electronics design generate <1ns time response

(Warner)
Installation on CM2 (FNAL)
Systems employing thermometry or calorimetry to monitor temperature of cryogenic components and vacuum chambers are being developed.

<table>
<thead>
<tr>
<th>Beam loss in cryomodule</th>
<th>0.1 W/m</th>
<th>1 W/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1K rising time</td>
<td>1 min</td>
<td>7 sec</td>
</tr>
<tr>
<td>Maximum temperature rising</td>
<td>1.83 K</td>
<td>8.9 K</td>
</tr>
<tr>
<td>Total rising time</td>
<td>30 min</td>
<td>20 min</td>
</tr>
</tbody>
</table>
Fast thermometry at aperture limits in SCL

Beam Loss Monitor Temperature Sensor Response

~30 sec to detect few mK

Time to first detect ΔT (sec)

Energy Deposited (J)

Average onset time: 50 mW = 29.1 s
Average onset time: 100 mW = 29.4 s

50 mW

100 mW

3 Cernox sensors mounted on pumping line, at ~10 mm intervals.

3 5Ω 20W heaters mounted diametrically opposite the temperature sensors, and at the same intervals.
Fast thermometry at aperture limits in SCL

Faster detection requires:
- ~mK resolution/stability
- More sophisticated DAQ (e.g., Fermilab FTS – 1-10 kHz timing, mK resolution)

~30 sec to detect few mK

Diagnostics for High Power Accelerator Machine Protection Systems, Slide 30
Fast thermometry at aperture limits in SCL Diagnostics for High Power Accelerator Machine Protection Systems, Slide 31

Faster detection requires
- ~mK resolution/stability
- More sophisticated DAQ (eg. Fermilab FTS – 1-10kHz timing, mK resolution)

Beam Loss Monitor Temperature Sensor Response

~30sec to detect few mK

3 5Ω 20W heaters mounted diametrically opposite the temperature sensors, and at the same intervals

3 Cernox sensors mounted on pumping line, at ~10mm intervals.

Pumping line flange

Bellows to cavity

Diagnostics for High Power Accelerator Machine Protection Systems, Slide 31
Direct beam diagnostics for fast detection

- Fast detection and beam interdiction requires accurate and robust measurements at time scales down to 1-10 µs
  - Detection and interdiction time is inversely proportional to intensity

- Beam current measurements
  - Robust monitoring at 1-10% of nominal level on

- Beam position monitors
  - Orbit shifts, intensity calibration

- Capacitive pickups and current sensing intercepting devices
  - Halo loss rings
Beam current monitors (ACCTs, DCCTs)

Most current sensing of intense beams is conducted with AC or DC current transformers, with appropriate analog front end, analog-to-digital conversion, and digital signal processing.

The difference between ACCTs and DCCTs determine their optimal use.

- Low frequency response to DC
- Require offset correction
- Limited high frequency response

Good high frequency response
- Require frequent re-baselining
SNS Differential Beam Current Monitoring

- **Wideband CTs:**
  - 1 GHz with 1 ms droop time constant
  - Nearest one before and after SCL
  - Long cable lengths (500-1200ft)

Demonstration of fast MPS network to detect errant beams

Digital signal processing

Diagnostics for High Power Accelerator Machine Protection Systems 34
Abort test demonstrates improved response time

- Temporary change to the Machine Protect System
- DBCM will automatically abort in middle of the beam pulse
- Using slow and long cables
  → ~8.5µs abort time
  → 2-3x improvement
  → ~6µs best possible once optimized for cable length, pickup locations, and abort mechanism

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Diagnostics for High Power Accelerator Machine Protection Systems 35

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

International Beam Instrumentation Conference
Monterey, California, USA September 14–18, 2014
Low Energy Differential Beam Current Monitoring at Heavy Ion Facilities

Diagnostics for High Power Accelerator Machine Protection Systems
Beam position monitors have a natural place in MPS

- Denser network than BCMs
- Can monitor fast beam intensity changes, orbit deviations
- Suffer from position sensitivity and nonlinearity, low-β effects, differential gain drifts
- Narrow band RF receivers sensitive to bunch duration

\[ \sigma \approx 0.81 \, \text{mm} \]

\[ \sigma \approx 0.09 \, \text{mm} \]
Current measurements using BPMs (SNS)

- **Beam Position Monitor:**
  - Use sum from all four plates
  - Use demo log-amp board with band-pass filter in front
  - Add correction in FPGA with exponential function
  - Use existing BCM as reference for calibration

---

**RF Bandpass**

**Logamp**

**Sum signal**

**Log signal**

**FPGA code to correct log signal**

**Final signals. Calibration done using downstream BCM**
Low-β effect in FRIB

- at low beta, electric field spreads out longitudinally
  - reduces high frequency content
  - effect is larger with beam off center
  - exaggerates bpm position sensitivity
  - can’t be measured with wire

- Shafer – Low-beta (1993)
  - 50% gain error in MEBT
  - <2% after FS1
Low $\beta$ correction

- With correction, the rms error over the working aperture improves 20x.

\[ \sigma \sim 0.746 \text{ mm} \quad \sigma \sim 0.036 \text{ mm} \]
Halo Monitor Ring (HMR) detects loss by minimal interception

- The halo ring monitor is a niobium ring designed to intercept ions in the halo of the beam that are likely to be lost farther downstream.
- It has high sensitivity (~0.1 nA) for integrated small signal and fast response time (~10 µs) for large signal.
- Optimize aperture based on fault mode studies. Monitor signal for large beam excursions. Install in warm sections between cryomodules.

HMR measurement at NSCL with $^{18}$O$^{3+}$ at 11 MeV/u

(Liu)
Advantages of HMR at Low Energy Regime

- HMR signal does not suffer from radiation cross-talk and background
- Interception beam current signal >> ionization chamber signal

<table>
<thead>
<tr>
<th>Loss Mode</th>
<th>Loss Source Location</th>
<th>(^{238}\text{U} \text{ Energy / Charge} ) [(MeV/u) / Q]</th>
<th>Loss Level [W/m]</th>
<th>Ion Chamber Signal [pA]</th>
<th>HMR Intercepted Beam [nA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow loss</td>
<td>LS1</td>
<td>10 / 33+</td>
<td>1</td>
<td>0.003*</td>
<td>72 **</td>
</tr>
<tr>
<td></td>
<td>LS2</td>
<td>60 / 78+</td>
<td>1</td>
<td>0.3*</td>
<td>29 **</td>
</tr>
<tr>
<td></td>
<td>LS3</td>
<td>200 / 78+</td>
<td>1</td>
<td>4.2 ***</td>
<td>9 **</td>
</tr>
<tr>
<td>Fast loss</td>
<td>3(^{rd}) ⇐=0.29 cavity</td>
<td>20 / 78+</td>
<td>~1300 (in ~15m)</td>
<td>~7.0</td>
<td>29×10^3</td>
</tr>
</tbody>
</table>

* Assume the transfer function of ion chamber is 16.9 pA/R/hr (SNS).
** Assume HMR intercepts 1 W/m × 5 m beam power.
*** LS3 signal is calculated from loss in a superconducting structure.
### Proposed Beam Loss Detection Methods (FRIB)

<table>
<thead>
<tr>
<th>Fast Loss</th>
<th>LS1</th>
<th>FS1</th>
<th>LS2 low energy</th>
<th>LS2 high energy</th>
<th>FS2</th>
<th>LS3</th>
<th>BDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>DBCM</td>
<td>DBCM</td>
<td>DBCM</td>
<td>DBCM</td>
<td>DBCM</td>
<td>DBCM</td>
<td>DBCM</td>
</tr>
<tr>
<td>&lt; 35 µs</td>
<td>Secondary</td>
<td>HMR</td>
<td>HMR</td>
<td>BLM</td>
<td>BLM</td>
<td>BLM</td>
<td>BLM</td>
</tr>
<tr>
<td></td>
<td>Tertiary</td>
<td></td>
<td></td>
<td>HMR</td>
<td>HMR</td>
<td>HMR</td>
<td></td>
</tr>
<tr>
<td>Slow loss</td>
<td>Primary</td>
<td>HMR/Temp</td>
<td>HMR</td>
<td>BLM</td>
<td>BLM</td>
<td>BLM</td>
<td>BLM</td>
</tr>
<tr>
<td>&gt; 100 ms</td>
<td>Secondary</td>
<td>HMR/Temp</td>
<td>HMR/Temp</td>
<td>HMR/Temp</td>
<td>HMR/Temp</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tertiary</td>
<td>Cryo</td>
<td>HMR/Temp</td>
<td>HMR/Temp</td>
<td>HMR/Temp</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Diagnostics for High Power Accelerator Machine Protection Systems, Slide 44**
Layering of SPIRAL-2 detection method and time scales schemes
# Redundant, Multi-layered Machine Protection Responds to Fast Events and Slow Losses

<table>
<thead>
<tr>
<th>Mode</th>
<th>Response time</th>
<th>Main purpose and approach</th>
<th>Detection technique</th>
<th>Loss mitigation technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast protection system</td>
<td>~ 35 µs</td>
<td>• Prevent damage from acute beam loss by quickly activating the beam inhibit device;</td>
<td>• Low-Level RF controller; Dipole current monitor; Differential BCM; Ion chamber; Halo monitor ring; Fast neutron detector; Differential BPM</td>
<td>• LEBT bend electrostatic deflector</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Lower sensitivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run permit system [1]</td>
<td>~ 100 ms</td>
<td>• Continuously queries the machine state and provides permission to operate with beam</td>
<td>• Vacuum; Cryomodule status; Non-dipole magnet PS; Interceptive diagnostics; Differential BCM; Quench signal; Differential BPM; Ion chamber; Slow neutron detector</td>
<td>• LEBT bend electrostatic deflector; ECR source HV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run permit system [2]</td>
<td>&gt; 1 s</td>
<td>• Prevent slow degradation of SRF system under small beam loss; Require high sensitivity detection</td>
<td>• Thermo-sensor near solenoids for beam loss monitoring; Cryogenic heater power</td>
<td>• LEBT bend e- deflector; ECR source HV</td>
</tr>
</tbody>
</table>
MPS Timescales at LHC, 40 $\mu$s to 84 s

<table>
<thead>
<tr>
<th>Signal Name</th>
<th>Time Window</th>
<th>Refreshing Rate</th>
<th>Data Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS1</td>
<td>0.04</td>
<td>0.04</td>
<td>max.</td>
</tr>
<tr>
<td>RS2</td>
<td>0.08</td>
<td>0.04</td>
<td>max.</td>
</tr>
<tr>
<td>RS3</td>
<td>0.32</td>
<td>0.04</td>
<td>max.</td>
</tr>
<tr>
<td>RS4</td>
<td>0.64</td>
<td>0.04</td>
<td>max.</td>
</tr>
<tr>
<td>RS5</td>
<td>2.56</td>
<td>0.08</td>
<td>max.</td>
</tr>
<tr>
<td>RS6</td>
<td>10.24</td>
<td>0.08</td>
<td>max.</td>
</tr>
<tr>
<td>RS7</td>
<td>81.02</td>
<td>2.56</td>
<td>max.</td>
</tr>
<tr>
<td>RS8</td>
<td>655.36</td>
<td>655.36</td>
<td>max.</td>
</tr>
<tr>
<td>RS9</td>
<td>1310.72</td>
<td>81.92</td>
<td>surr.</td>
</tr>
<tr>
<td>RS10</td>
<td>5242.88</td>
<td>81.92</td>
<td>surr.</td>
</tr>
<tr>
<td>RS11</td>
<td>20971.52</td>
<td>655.36</td>
<td>surr.</td>
</tr>
<tr>
<td>RS12</td>
<td>83886.06</td>
<td>655.36</td>
<td>surr.</td>
</tr>
</tbody>
</table>

- **1 turn** = 89 $\mu$s
- **10 turns** = 0.89 s
- **100 turns**
- **1000 turns**
- **10000 turns** = 0.89 s

**Operational ‘mistakes’**
- Kicker magnets
- Quenches
- NC magnet powering failures
- Power converter interlocks
- FMCM
- Absorbers

**Diagnostics for High Power Accelerator Machine Protection Systems**, Slide 47

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FRIIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

International Beam Instrumentation Conference
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Summary

- Elements of modern MPS design for high power hadron machines have been presented.
- Modes of beam loss, and detection techniques were discussed.
- Differential beam current monitoring is beginning to eclipse beam loss monitoring as the primary detection scheme.
- Integrating and layering schemes with multiple time-scales and redundant detection mechanisms is necessary for reliable and robust operation.
- Incorporation of beam loss detection with other cryomodule instrumentation will tax heat load budgets but must be pursued.
- Simulation, modeling, network building can optimize monitor placement and assist event post-mortem analysis.
Acknowledgment

- Participants of the 2014 Machine Protection Systems for High Power Superconducting Hadron Accelerators Workshop


Thank You
Mixed radiation fields

Measured spectra at CERF

<table>
<thead>
<tr>
<th>Particle composition in %</th>
<th>$\pi^+$</th>
<th>protons</th>
<th>K$^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60.7</td>
<td>34.8</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Momentum | 120 GeV/c

Intensity used | up to $9.5 \times 10^7$ hadrons (4000 PIC) per 16.8 s

Gaussian beam shape approximation (4000 PIC)

- $\sigma_{\text{horizontal}}$: 1.3 cm
- $\sigma_{\text{vertical}}$: 1.0 cm
 Cryomodule – Operating Temperature

- 2 K generally refers to liquid helium temperature from 1.8 K to 2.1 K
- Temperature difference is relatively small, but the difference of pressure is significant: from 1.6 kPa to 4.1 kPa, so are costs of cryoplant and operation
- Operational temperature of the FRIB cavity is under evaluation

Phase diagram of helium

Lambda point: 5.05 kPa, 2.177 K

Diagnostics for High Power Accelerator Machine Protection Systems, Slide 51
Pressure builds up with the depth of helium bath, so as the saturation temperature $T_s$.

The maximum surface temperature $T_{\text{max}}$ should be below the saturation and Lambda point.

In the current design of the helium vessel, heat flux in the cavity is minimized.

$T_{\text{max}}$ is estimated with a constant flux of 0.5 W/cm$^2$, gradient $\sim$ 0.1 mK/cm.

### Table: LHe Pressure and Temperature Correlation Studied

<table>
<thead>
<tr>
<th>Pos.</th>
<th>P (Pa)</th>
<th>$T_s$ (K)</th>
<th>$T_{\text{max}}$ (K)</th>
<th>h (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4141</td>
<td>2.100</td>
<td>2.100</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>4427</td>
<td>2.123</td>
<td>2.102</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>5572</td>
<td>2.218</td>
<td>2.111</td>
<td>100</td>
</tr>
<tr>
<td>D</td>
<td>5858</td>
<td>2.240</td>
<td>2.113</td>
<td>120</td>
</tr>
</tbody>
</table>

For HWR:

<table>
<thead>
<tr>
<th>Pos.</th>
<th>P (Pa)</th>
<th>$T_s$ (K)</th>
<th>$T_{\text{max}}$ (K)</th>
<th>h (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4141</td>
<td>2.100</td>
<td>2.100</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>4427</td>
<td>2.123</td>
<td>2.102</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>5785</td>
<td>2.154</td>
<td>2.107</td>
<td>45</td>
</tr>
<tr>
<td>D</td>
<td>5142</td>
<td>2.184</td>
<td>2.110</td>
<td>70</td>
</tr>
</tbody>
</table>
Design Example of DBCM (Bergoz BCM)

- Example: LS1 differential currents
  - Current difference measurements are performed in <10 µs with a current resolution better than 4 µA (~1% of full beam current)

<table>
<thead>
<tr>
<th>Beamline Segment</th>
<th>Time of flight (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEBT</td>
<td>1.3</td>
</tr>
<tr>
<td>RFQ</td>
<td>0.7</td>
</tr>
<tr>
<td>MEBT</td>
<td>0.7</td>
</tr>
<tr>
<td>LS1</td>
<td>2.4</td>
</tr>
<tr>
<td>FS1</td>
<td>1.4</td>
</tr>
<tr>
<td>LS2</td>
<td>1.2</td>
</tr>
<tr>
<td>FS2</td>
<td>0.3</td>
</tr>
<tr>
<td>LS3 and BDS</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Individual nodes to digitize and filter the transformer signals, to perform digital processing to recover the beam current, and to compute integrated current values.

Dedicated data links to master controller to compute differential current information.
Differential Current Monitoring by BPM Pair

- Experiment was set up at ReA3 with Fermilab BPM receivers
  - Measures second harmonic 161 MHz
  - 81 dB gain pre-amp; 1.32 dB cable loss
  - Effective BW ~37kHz (τ~4.3µs)

- For 37 kHz, the calculated intensity RMS resolution (std) is 126 nA.

- From experiment, the RMS intensity resolution (std) for single BPM is measured as 67-106 nA for 204800 samples, assuming beam is at the center. The differential intensity resolution is ~140 nA.

- FRIB BPM intensity resolution is comparable with ReA3 BPM, and it features fast evaluation (~15µs).

- BPM resolution is very sensitive to beam position and beam velocity. Calibration is necessary.
Prototype HMR Test Set-up at NSCL

Diagnostics for High Power Accelerator Machine Protection Systems

SHV Feedthru
BNC Feedthru
TC Feedthru
Teflon wire 600V, 200 °C
J-Type TC Ungrounded
~40 ft RG-59 cable
Keithley picoammeter 6487 with 500V voltage source

Solenoid
Pin outs
MODICON
Control Network